

Forward-backward elliptic anisotropy correlation in parton cascade

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(Dated: January 14, 2013)

A potential experimental probe, forward-backward elliptic anisotropy correlation (C_{FB}), has been proposed by Liao and Koch to distinguish the jet and true elliptic flow contribution to the measured elliptic flow (v_2) in relativistic heavy-ion collisions. Jet and flow fluctuation contribution to elliptic flow is investigated within the framework of a multi-phase transport model using the C_{FB} probe. We found that the C_{FB} correlation is remarkably different and is about two times of that proposed by Liao and Koch. It originates from the correlation between fluctuation of forward and backward elliptic flow at low transverse momentum, which is mainly due to the initial correlation between fluctuation of forward and backward eccentricity. This results in an amendment of the C_{FB} by a term related to the correlation between fluctuation of forward and backward elliptic flow. Our results suggest that a suitable rapidity gap for C_{FB} correlation studies should be around ± 3.5 .

PACS numbers: 12.38.Mh, 25.75.Gz, 25.75.Ld

The results from Brookhaven Relativistic Heavy-Ion Collider (RHIC) indicate that a strongly-interacting partonic matter has been created in relativistic nucleus-nucleus collisions [1]. Two powerful probes exposing the characteristics of the new matter are elliptic flow and jet. Elliptic flow, has been measured via the second Fourier coefficient (v_2) in the azimuthal distribution of final particles [2, 3]. The v_2 data show remarkable hydrodynamical behaviors, which implies the formed matter is thermalized in a very short time and expands collectively as a liquid with low shear viscosity/entropy. On the other hand, jet, which is produced non-collectively by initial hard scatterings, has been experimentally studied by nuclear modification factor and jet-like correlation [4–10]. These observation shows that jet losses energy when it passes through the hot and dense QCD medium formed in heavy-ion collisions. However, two probes, elliptic flow and jet, are correlated in fact. The jet contributes to the anisotropy in final azimuthal distribution and certainly to the observed v_2 , especially for high transverse momentum (p_T) because of the path length dependence of energy loss in non-central collisions [11, 12]. Nuclear community usually classify such a non-collective behavior as non-flow. Therefore, it is important for elliptic flow measurement to distinguish these two parts from observed v_2 to further separate collective and non-collective properties of the new matter. A potential experimental probe, forward-backward elliptic anisotropy correlation (C_{FB}), has been proposed for this purpose by Liao and Koch (LK) [13]. It is believed that the new probe can distinguish how jet and elliptic flow contribute to the observed v_2 which probably reveal the momentum scale where elliptic flow or (semi-) hard processes dominate. Using a two-component parameterization, they found the F-B correlation (C_{FB}), which takes a maximum value of unity

at low transverse momentum (p_T) and falls to zero with p_T . This indicates the jet contribution to the measured v_2 grows with increasing p_T and even jet contribution dominates at high p_T . However, event-by-event fluctuation of v_2 is also important for v_2 measurement [12, 14]. Experimental data shows that the relative nonstatistical fluctuations of the v_2 is to be approximately 40% [14]. Unfortunately it is not taken into account in LK's calculation. Our present study considers the effect of v_2 fluctuation to further understand bulk properties and related jet effects in the early stage of heavy-ion collisions. Our paper presents the relative nonstatistical fluctuation effects on the forward-backward v_2 correlation (C_{FB}) and the G -factor range which reflects jet contribution to observed v_2 with a multi-phase transport model (AMPT) [15]. A more generalized C_{FB} which includes F-B elliptic flow fluctuation correlation is formulated.

The AMPT model consists of four main components: the initial conditions, partonic interactions, conversion from partonic to hadronic matter and hadronic interactions. The initial conditions, which include the spatial and momentum distributions of minijet partons and soft string excitations, are obtained from the Heavy Ion Jet Interaction Generator model. Scatterings among partons are modeled by Zhang's Parton Cascade model, which at present includes only two-body scatterings in which cross sections are obtained from the pQCD calculation by screening mass. In the version with string melting mechanism, partons include minijet partons and partons from melted strings. The quark coalescence model is used to convert partons into hadrons. The dynamics of the subsequent hadronic matter is then described by a relativistic transport model. The detail of the AMPT model can be found in Ref. [15]. From the previous AMPT calculations, it is found that elliptic flow can be built by strong parton cascade [3, 15–19] and jet losses energy into partonic medium to excite a Mach-like cone structure [20–22]. It is clear from the above that partonic effect can not be neglected. Therefore the string melting

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AMPT version is appropriate when the energy density is much higher than the critical density which is predicted for phase transition. In this work, we use the string melting AMPT model to simulate Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The partonic interaction cross section is set to 10 mb.

Elliptic flow v_2 is defined as

$$\langle v_2(p_T) \rangle = \frac{\int_0^{2\pi} d\phi \cos 2\phi \langle \frac{d^2 N}{p_t dp_t d\phi} \rangle}{\int_0^{2\pi} d\phi \langle \frac{d^2 N}{p_t dp_t d\phi} \rangle} \equiv \frac{\langle V_2(p_t) \rangle}{\langle \frac{dN}{p_t dp_t} \rangle}, \quad (1)$$

where the total yields $\frac{d^2 N}{p_t dp_t d\phi}$ are resulted from both elliptic flow and jet [13] which then contribute to the measured v_2 .

The proposed observable $C_{FB}[p_T]$ is the correlation of the total elliptic flow $V_2[p_T]$ between forward (F) and backward (B) rapidity bins [13], defined as:

$$C_{FB}[p_T] = \frac{\langle V_2^F V_2^B \rangle}{\langle V_2^F \rangle \langle V_2^B \rangle}. \quad (2)$$

With the assumption $\langle \eta^F \rangle = \langle \eta^B \rangle = 0$, $\langle \xi \rangle = \langle 1 - \xi \rangle = \frac{1}{2}$ and $\xi(1 - \xi) = 0$, C_{FB} changes to

$$C_{FB} = \frac{(1-g)^2 \langle v_2^f \rangle^2 + 2g(1-g) \langle v_2^f \rangle \langle v_2^j \rangle}{[(1-g) \langle v_2^f \rangle + g \langle v_2^j \rangle]^2} + \frac{4 \langle \eta^F \eta^B \rangle (1-g)^2 \langle v_2^f \rangle^2}{[(1-g) \langle v_2^f \rangle + g \langle v_2^j \rangle]^2}, \quad (3)$$

where $\eta^{F(B)}$ represents random deviations from the average elliptic flow yield in forward (backward) rapidity bin, $v_2^{f(j)}$ represents elliptic flow (jet) part in v_2 , ξ represents the jet contribution to F or B rapidity bin, and g factor, giving the relative weight of the jet contribution to the total, i.e. (F+B), yield, is defined as [13]

$$g = \frac{\int_0^{2\pi} d\phi \langle \frac{dN^j}{d\phi} \rangle}{\int_0^{2\pi} d\phi \langle \frac{dN^f}{d\phi} \rangle + \int_0^{2\pi} d\phi \langle \frac{dN^j}{d\phi} \rangle}. \quad (4)$$

When the correlation of the fluctuation of F-B elliptic flow yield is zero, (i.e. $\langle \eta^F \eta^B \rangle = 0$), then LK found:

$$C_{FB} = \frac{(1-g)^2 \langle v_2^f \rangle^2 + 2g(1-g) \langle v_2^f \rangle \langle v_2^j \rangle}{[(1-g) \langle v_2^f \rangle + g \langle v_2^j \rangle]^2}. \quad (5)$$

When only jet contributes to v_2 , that is $g = 1$, $C_{FB} = 0$; On the other hand, if only elliptic flow contributes to v_2 , then $g = 0$, $C_{FB} = 1$.

However, if the correlation of the fluctuation of F-B elliptic flow is nonzero and for example $\langle \eta^F \eta^B \rangle = \frac{1}{4}$, C_{FB} will change to

$$C_{FB} = \frac{2(1-g)^2 \langle v_2^f \rangle^2 + 2g(1-g) \langle v_2^f \rangle \langle v_2^j \rangle}{[(1-g) \langle v_2^f \rangle + g \langle v_2^j \rangle]^2}. \quad (6)$$

When only jet contributes to v_2 , then $g = 1$, $C_{FB} = 0$; However, if only elliptic flow contributes to v_2 , then $g = 0$, $C_{FB} = 2$.

We introduce a G factor to represent total jet contribution V_2^j to total $V_2(p_T)$, which has a relation to g factor in [13] as followed:

$$G = \frac{\langle v_2^j \rangle \int_0^{2\pi} d\phi \langle \frac{dN^j}{d\phi} \rangle}{\langle v_2 \rangle (\int_0^{2\pi} d\phi \langle \frac{dN^f}{d\phi} \rangle + \int_0^{2\pi} d\phi \langle \frac{dN^j}{d\phi} \rangle)} = \frac{v_2^j}{v_2} g. \quad (7)$$

Using a different form of total $V_2(p_T)$ in forward (F) and backward (B) rapidity bins, i.e. $V_2^F = (\frac{1}{2} + \eta^F)(1 - G)\langle V_2 \rangle + \xi G\langle V_2 \rangle$ and $V_2^B = (\frac{1}{2} + \eta^B)(1 - G)\langle V_2 \rangle + (1 - \xi)G\langle V_2 \rangle$, we get the formula below with the assumption $\langle \eta^F \rangle = \langle \eta^B \rangle = 0$, $\langle \xi \rangle = \langle 1 - \xi \rangle = \frac{1}{2}$, and $\xi(1 - \xi) = 0$, but $\langle \eta^F \eta^B \rangle \neq 0$:

$$C_{FB} = 1 - G^2 + 4(1 - G)^2 \langle \eta^F \eta^B \rangle. \quad (8)$$

When the correlation of the fluctuation of F-B elliptic flow is zero, (i.e. $\langle \eta^F \eta^B \rangle = 0$), $C_{FB} = 1 - G^2$. From here, only jet will contribute to v_2 when $G = 1$, $C_{FB} = 0$. On the other hand, only elliptic flow contributes to v_2 when $G = 0$, $C_{FB} = 1$. While when the correlation is nonzero, for example $\langle \eta^F \eta^B \rangle = \frac{1}{4}$, $C_{FB} = 2(1 - G)$. Then we can find that only jet contributes to v_2 with a condition $G = 1$, $C_{FB} = 0$. However, only elliptic flow will contribute to v_2 when $G = 0$, $C_{FB} = 2$.

The current v_2 measurement can not distinguish the deviations of elliptic flow $\eta^{F(B)}$ from jet effect of ξ in experiment, since they are mixed together. One can redefine total $V_2(p_T)$ in forward (F) and backward (B) rapidity bins, $V_2^F = (1 + \eta_F^{all})\langle V_2^F \rangle$, and $V_2^B = (1 + \eta_B^{all})\langle V_2^B \rangle$, where $\eta_{F(B)}^{all}$ includes the fluctuation of elliptic flow and jet contribution. The F-B correlation can be rewritten as:

$$C_{FB} = \frac{1 + \langle \eta_F^{all} \rangle + \langle \eta_B^{all} \rangle + \langle \eta_F^{all} \eta_B^{all} \rangle}{1 + \langle \eta_F^{all} \rangle + \langle \eta_B^{all} \rangle + \langle \eta_F^{all} \rangle \langle \eta_B^{all} \rangle}. \quad (9)$$

With the assumption $\langle \eta_F^{all} \rangle = \langle \eta_B^{all} \rangle = 0$, we can finally get the same expression as Eq. (8).

C_{FB} has been simulated by using AMPT model for Au+Au at $\sqrt{s_{NN}} = 200$ GeV at the centrality bin 0-20%. The results are shown in Fig. 1, where different symbols represent different forward and backward pseudo-rapidity bins. For example, $0.5 < |\eta| < 1.0$ represents that the forward bin is within $0.5 < \eta < 1.0$ and while the backward bin is within $-1.0 < \eta < -0.5$. C_{FB} remains constant for different rapidity gaps at low p_T ($p_T < 2$ GeV/c) in 0-20% centrality bin. To our surprise, C_{FB} appears to be remarkably different from the prediction of Ref. [13], nearly two times as LK's (unity) at low p_T ($p_T < 2$ GeV/c) for the mid-rapidity gap, and decreases with rapidity gap. The reason, as shown in Eq. (6) and (8), is that the correlation of the fluctuation of F-B elliptic flow $\langle \eta^F \eta^B \rangle$ is nonzero, i.e. $\langle \eta^F \eta^B \rangle$ is close to $\frac{1}{4}$ at low p_T for mid-rapidity gap at 0-20% centrality bin. As rapidity gap rises to 7.0 (Fig. 1(b)), C_{FB} falls to 1.2, which indicates $\langle \eta^F \eta^B \rangle$ becomes weak for a large rapidity gap.

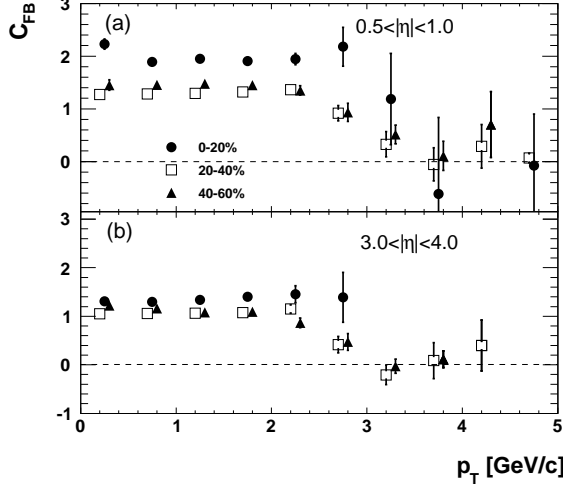


FIG. 1: C_{FB} for 200 GeV/c Au + Au collisions at 0-20% (circles), 20-40% (squares), and 40-60% (triangle) centrality bins. (a) $0.5 < |\eta| < 1.0$, and (b) $3.0 < |\eta| < 4.0$ (Some symbols are slightly shifted in p_T -axis for clarity).

Fig. 1 also displays that C_{FB} is much larger for central collisions than non-central collisions at low p_T , which indicates that F-B elliptic flow fluctuation is strongly correlated in the most central collisions. This trend is consistent with centrality dependence of elliptic flow fluctuation [24]. In addition, $\langle \eta^F \eta^B \rangle$ is near to a positive constant at low p_T for the given rapidity bins and centrality. However, at high p_T ($p_T > 4$ GeV/c), C_{FB} is close to zero, indicating that only jet contributes to the observable v_2 and $\langle \eta^F \eta^B \rangle$ is zero. The results are similar with LK's finding here. Therefore, $\langle \eta^F \eta^B \rangle$ should positively decrease in intermediate p_T region ($2 < p_T < 4$ GeV/c). It means that C_{FB} can not be used to directly measure the jet contribution to observed v_2 without the knowledge of $\langle \eta^F \eta^B \rangle$, especially for mid-rapidity gap.

The same trend is also seen in Fig. 1(b), rapidity bin $3.0 < |\eta| < 4.0$. For centrality bins 20-40% and 40-60%, C_{FB} looks near to unity at low p_T , which means $\langle \eta^F \eta^B \rangle$ is close to zero. The structures are similar with LK's finding here. Therefore, C_{FB} with large rapidity gap is a clean probe to extract jet contribution to elliptic flow, as Ref.[13] expected.

As we discussed in previous section, two limits of C_{FB} , i.e. $C_{FB} = 1 - G^2$ and $C_{FB} = 2(1 - G)$ which can be deduced assuming $\langle \eta^F \eta^B \rangle$ approaching to zero at high p_T or $\langle \eta^F \eta^B \rangle$ approaching to $\frac{1}{4}$ at low p_T , respectively. Fig. 2 shows the above two limits. We can see that the factor G , which reflects the jet contribution to the observed v_2 , cannot be strictly quantified by the observed C_{FB} . This gives only a range of G -value which can be estimated for mid-rapidity gap. This is due to the reason that we do not know the quantitative relation of $\langle \eta^F \eta^B \rangle$ and G for intermediate p_T region. With the decreasing of C_{FB} , the uncertain range of G becomes narrower.

On the other hand, elliptic flow, as is shown in Ref. [2, 25], is converted from initial collision geometry.

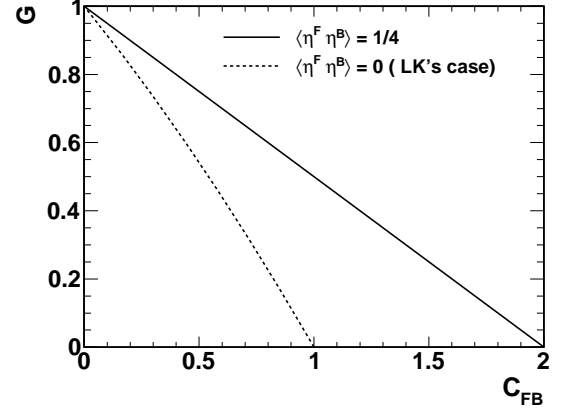


FIG. 2: The relation of G and C_{FB} for different F-B elliptic flow fluctuation correlation $\langle \eta^F \eta^B \rangle$ in 200 GeV/c Au + Au collisions, where $\langle \eta^F \eta^B \rangle = \frac{1}{4}$ corresponds to the case with rapidity gap $0.5 < |\eta| < 1.0$ at centrality bin 0-20%.

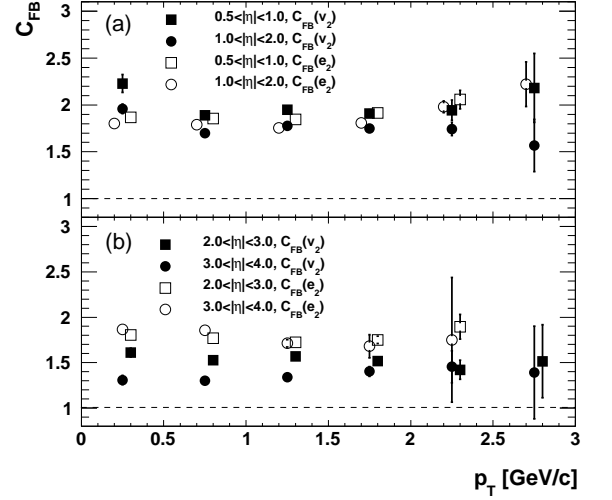


FIG. 3: C_{FB} for initial eccentricity (open symbols) and elliptic flow (solid symbols) in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV at centrality bin 0-20% within different rapidity gaps represented by different symbols. Some symbols are slightly shifted in p_T -axis for clarity).

It means that fluctuation of elliptic flow should reflect the information on fluctuation in the initial state geometry. Moreover, the fluctuation due to the magnitude and centrality dependence of observed elliptic flow are consistent with fluctuation of the initial geometry shape of the collision region [26]. It has been found that such a initial geometry irregularity can be transferred into final momentum anisotropies by strong partonic interactions [22, 27] (eg. triangular flow). It becomes more interesting to compare C_{FB} for elliptic flow (v_2) and initial

eccentricity (e_2).

In AMPT model, partons, which are melted from string, are initially distributed in momentum and coordinate spaces. We can similarly define C_{FB} for initial eccentricity (e_2) as $C_{FB}(e_2) = \frac{\langle E_2^F E_2^B \rangle}{\langle E_2^F \rangle \langle E_2^B \rangle}$, where $E_2^{F(B)}$ are the total eccentricity (E_2) in forward (F) and backward (B) rapidity bins, and $\langle E_2(p_T) \rangle = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \langle \frac{dN}{p_t dp_t} \rangle$.

Similar to $V_2^{F(B)}$, $E_2^{F(B)}$ can be written as $E_2^F = (\frac{1}{2} + \eta'_F) \langle E_2 \rangle$ and $E_2^B = (\frac{1}{2} + \eta'_B) \langle E_2 \rangle$, where $\eta'_{F(B)}$ represents random deviations from the total eccentricity in forward (backward) rapidity bin. If one compare with the former analysis of v_2 , $C_{FB}(e_2)$ presents similar trend to $C_{FB}(v_2)$, if the correlation between fluctuation of forward and backward elliptic flow is mainly due to the initial correlation between fluctuation of forward and backward eccentricity.

As shown in Fig. 3(a), it is an obvious fact that $C_{FB}(v_2)$ is efficiently transferred from $C_{FB}(e_2)$ at small rapidity gap. However, at large rapidity gap (in Fig. 3(b)), $C_{FB}(v_2)$ is suppressed much deeply in contrast to $C_{FB}(e_2)$. This indicates that parton cascade are not strong enough for larger rapidity gap to transfer the F-B correlation of initial e_2 fluctuation to final F-B correlation of v_2 fluctuation. This is because of the fact that parton interactions are weak at higher rapidity. There-

fore, the measurement of C_{FB} for elliptic flow (v_2) may give us more information about the correlation of initial geometry fluctuation.

In conclusion, jet and flow fluctuation contribution to elliptic flow are investigated by forward-backward elliptic anisotropy correlation (C_{FB}) within the framework of a multi-phase transport model. We found that the C_{FB} correlation is remarkably different from LK's and is about nearly double of that proposed by Liao and Koch. It stems from the correlation between fluctuation of forward and backward elliptic flow at low transverse momentum, which is mainly due to the initial correlation between fluctuation of forward and backward eccentricity. This leads to an amendment of the C_{FB} by a term related to the correlation between the fluctuation of forward and backward elliptic flow. The present study shows that C_{FB} correlation decreases with rapidity gap and a suitable rapidity gap for C_{FB} correlation studies should be around ± 3.5 .

This work was supported in part by the NSFC of China under Grant No. 11035009, 10979074, 10875159, and the Shanghai Development Foundation for Science and Technology under contract No. 09JC1416800, and the Knowledge Innovation Project of the Chinese Academy of Sciences under Grant No. KJCX2-EW-N01.

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